Metasurfaces with Reconfigurable Reflection Phase for High-Power Microwave Applications

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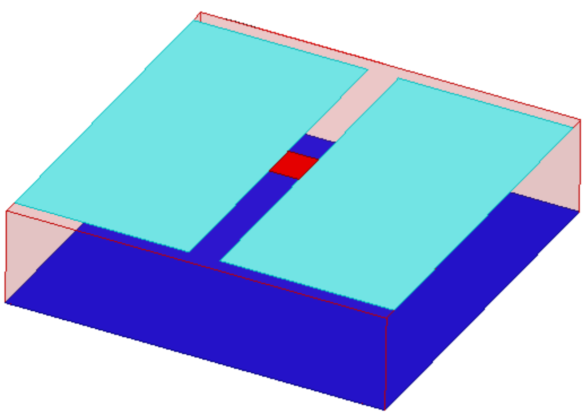

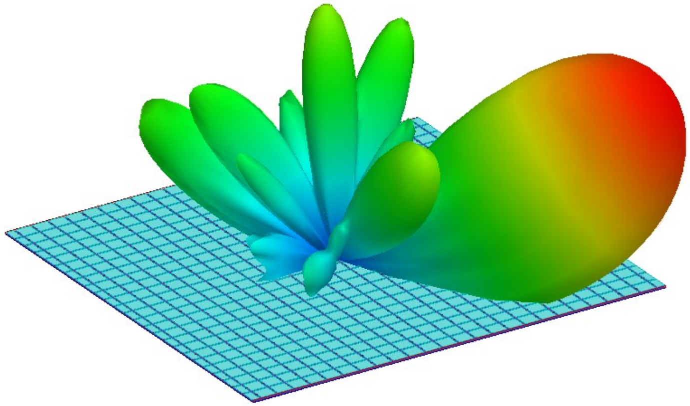

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14. ABSTRACT
Summary
Examples that demonstrate theoretical methods for extending the operating power levels of metasurface reflectarrays have been given
•The proposed designs provide the same utility that has been previously demonstrated, however are capable of operating at much higher power levels
Future Work
•Investigate additional electrically-tunable alternatives
•Demonstrate mechanically tunable reflect-array metasurface
–Fabrication and testing of a static prototype with predetermined super cell heights to form gradient phase distribution producing a desired reflected beam
–Investigation of mechanical systems capable of reconfiguring ground plane without significant performance impacts

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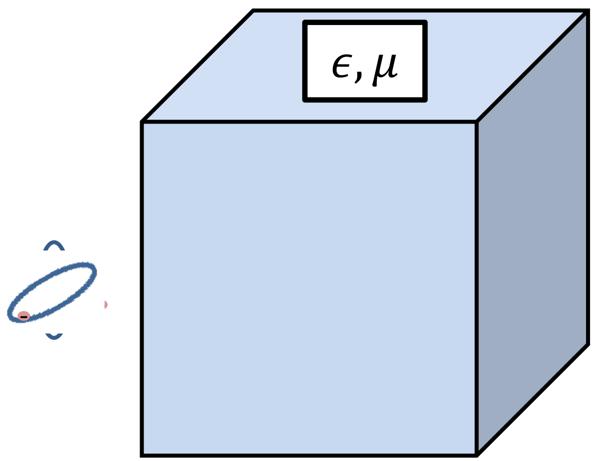
Outline

- Introduction
  - High-Power Microwave Systems
  - Metamaterials (Static and Tunable)
- Electrically Tunable Metasurfaces
  - PIN Diode-Based Capacitor Network
  - Varactor-Based
- Mechanically Reconfigurable Metasurface
  - Design
  - Analysis
- Closing Remarks

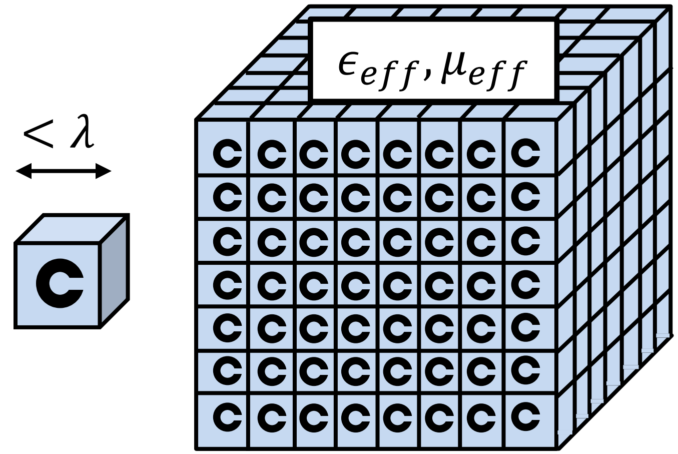
INTRODUCTION

Electromagnetic Metamaterials

Natural Materials

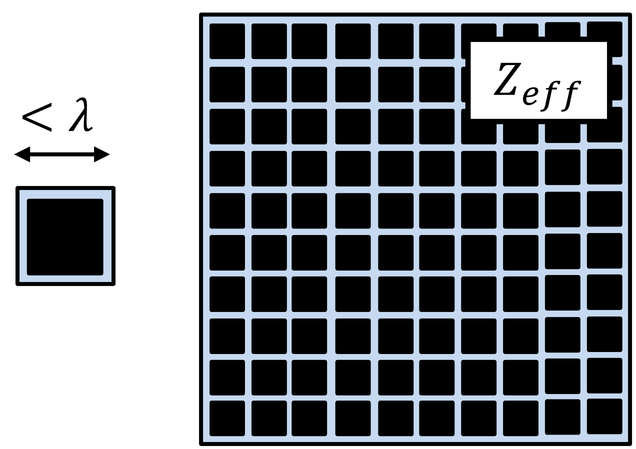


Bulk Metamaterial



- Natural materials rely on atomic/molecular interactions described by permittivity ϵ, and permeability μ.
- Metamaterials are artificial structures that can be engineered to exhibit extraordinary electromagnetic properties
  - Bulk metamaterials rely on interaction with sub-wavelength structures described by effective permittivity and permeability
  - Planar metamaterials (metasurfaces) are described by effective surface impedances

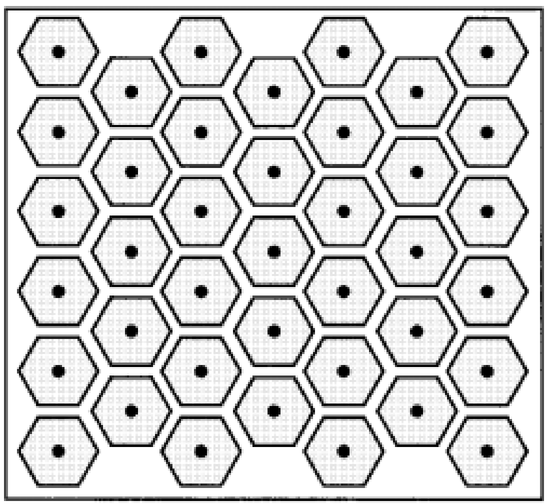
Planar Metamaterial

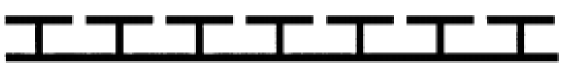


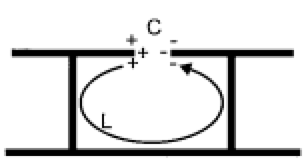
Artificial Magnetic Conductors (AMC)

High-Impedance Electromagnetic Surfaces with a Forbidden Frequency Band

Dan Sievenpiper, *Member, IEEE,* Lijun Zhang, Romulo F. Jimenez Broas, Nicholas G. Alexópolous, *Fellow, IEEE,* and Eli Yablonovitch, *Fellow, IEEE*

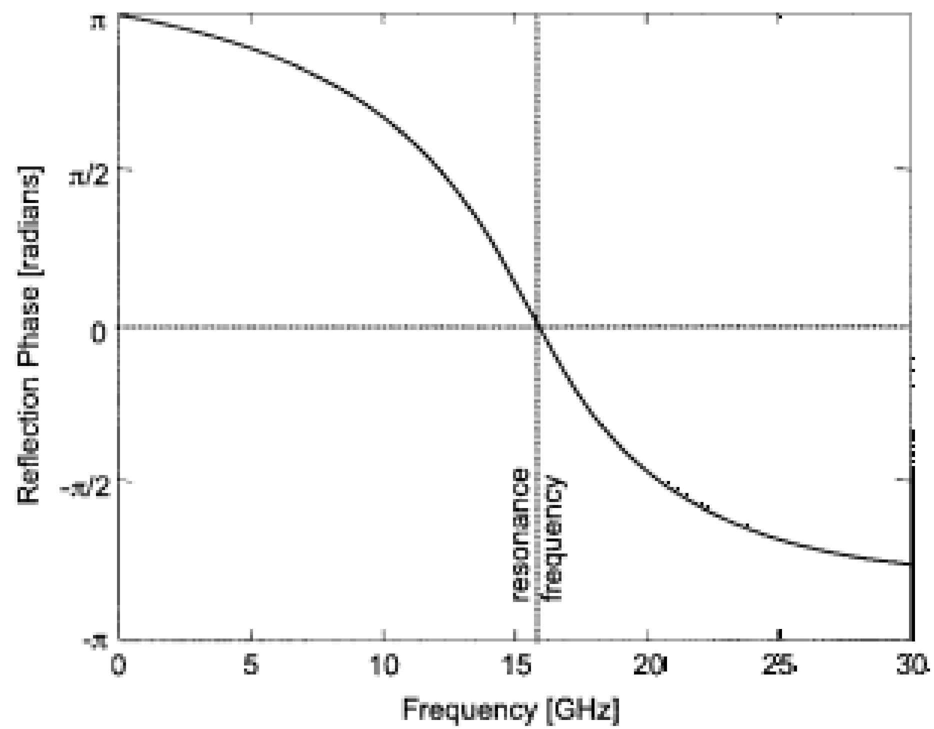






$$\omega_0 = \frac{1}{\sqrt{LC}}$$

$$Z_{surface} = \frac{j\omega L}{1 - \omega^2 LC}$$



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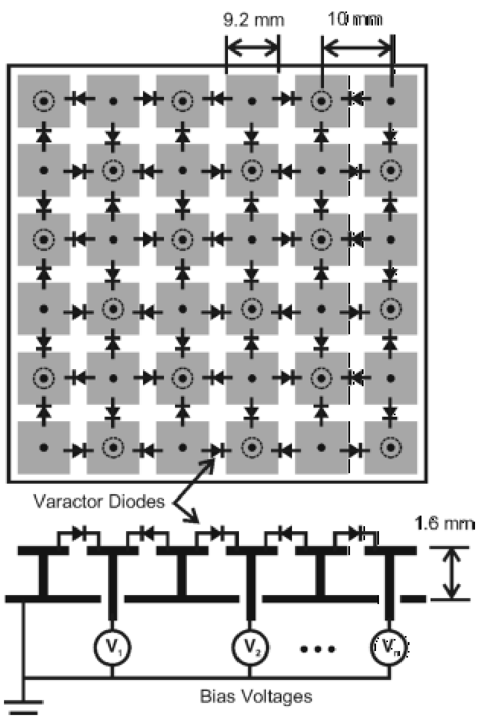
Previous Reflectarray Designs

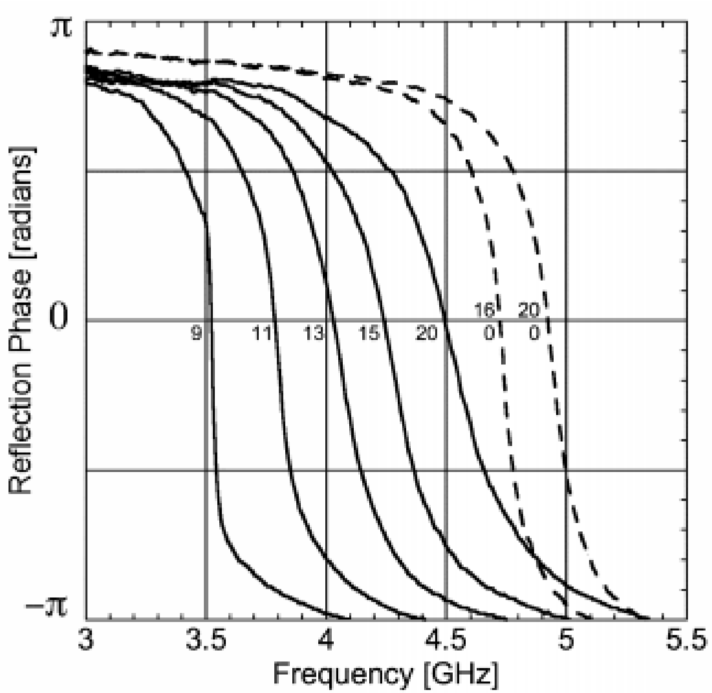
- Extend the utility of static metamaterial structures and can alleviate bandwidth limitations and fabrication tolerances
- Offer analogous functionality to reflect-array antennas for beam steering
- Tuning typically achieved using varactor diodes

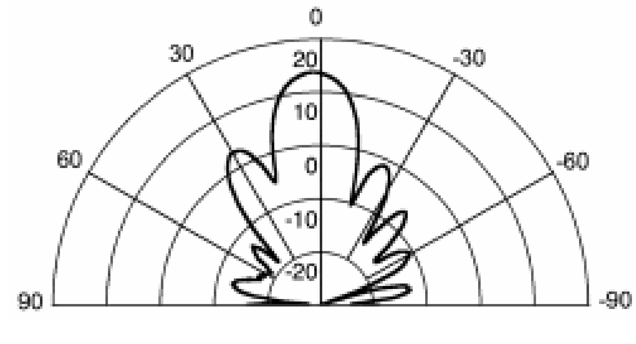
IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 51, NO. 10, OCTOBER 2003 2713

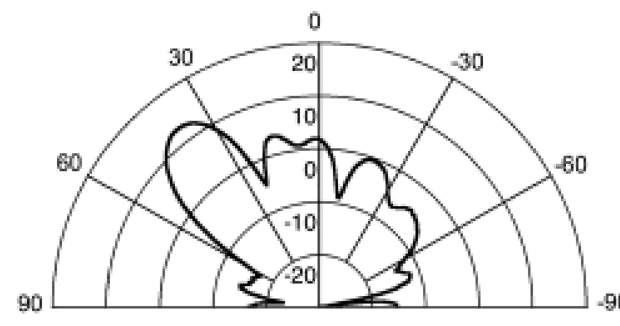
Two-Dimensional Beam Steering Using an Electrically Tunable Impedance Surface

Daniel F. Sievenpiper, *Member, IEEE*, James H. Schaffner, *Senior Member, IEEE*, H. Jae Song, *Member, IEEE*, Robert Y. Loo, *Member, IEEE*, and Gregory Tangonan, *Member, IEEE*







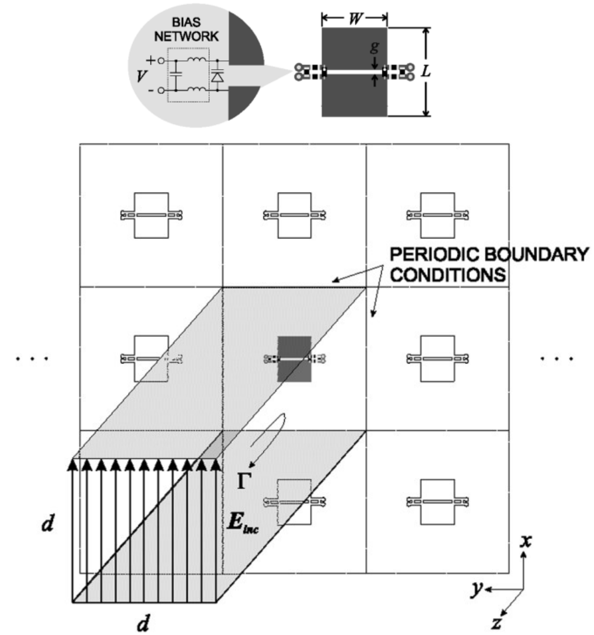


Previous Reflectarray Designs

2200 IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 55, NO. 8, AUGUST 2007

Modeling and Design of Electronically Tunable Reflectarrays

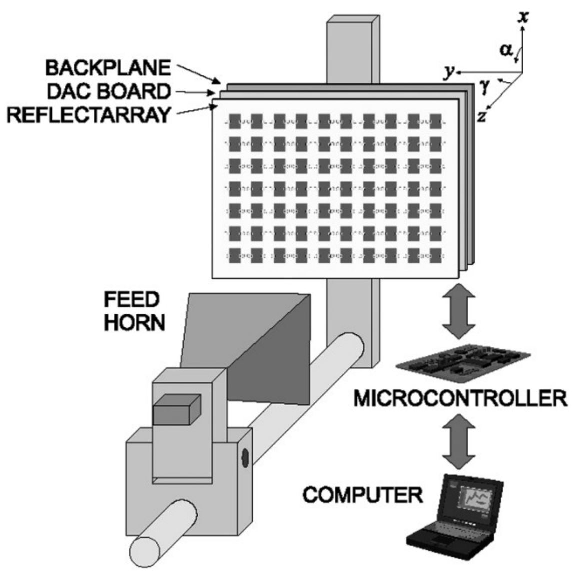
Sean Victor Hum, *Member, IEEE*, Michal Okoniewski, *Senior Member, IEEE*, and Robert J. Davies, *Member, IEEE*

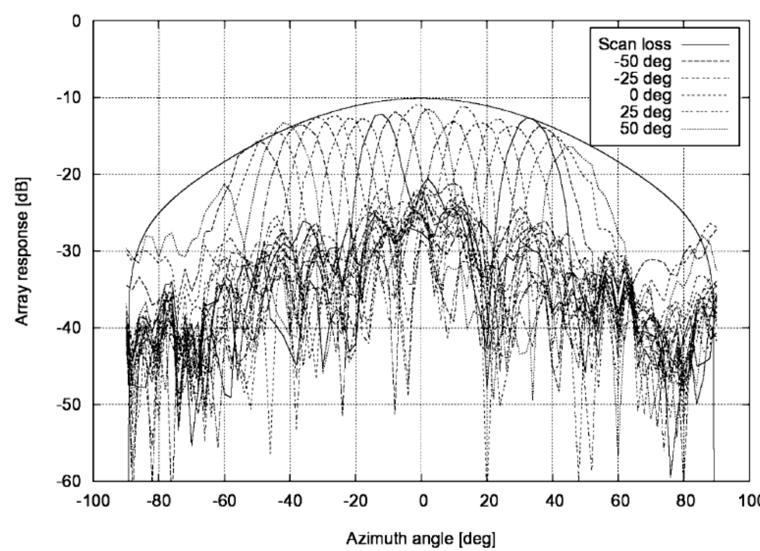


- Design with 320° of phase agility at ~5.8 GHz
- Little consideration given to power handling
- Significant loss from tuning elements (varactors)

TABLE II
REFLECTARRAY LOSS BUDGET ($\alpha_0 = 83.5°, \gamma_0 = 20°$)

Loss factor	Amount
1. Element absorption (ε_a)	1.8 dB
2. Phase error loss (ε_p)	0.8 dB
3. Element factor loss ($\lvert EF(\theta,\phi)\rvert$)	0.8 dB
4. Subtended aperture loss ($\cos\theta$)	0.3 dB
5. Illumination efficiency ($\varepsilon_{ill} = 0.43$)	3.7 dB
Total	7.4 dB





Metamaterial Reflect-Array

- Metasurfaces can provide the same functionality as conventional reflect-arrays but in a compact and cost-effective system
- Synthesis of a metasurface reflect-array is based on fundamental design equations for typical antenna arrays

$$Array\ Factor_{Normalized} = \left[\frac{1}{M}\frac{\sin\left(\frac{1}{2}M\Psi_x\right)}{\sin\left(\frac{1}{2}\Psi_x\right)}\right]\left[\frac{1}{N}\frac{\sin\left(\frac{1}{2}N\Psi_y\right)}{\sin\left(\frac{1}{2}\Psi_y\right)}\right]$$

$$\Psi_x = kd_x sin\theta cos\phi + \beta_x$$

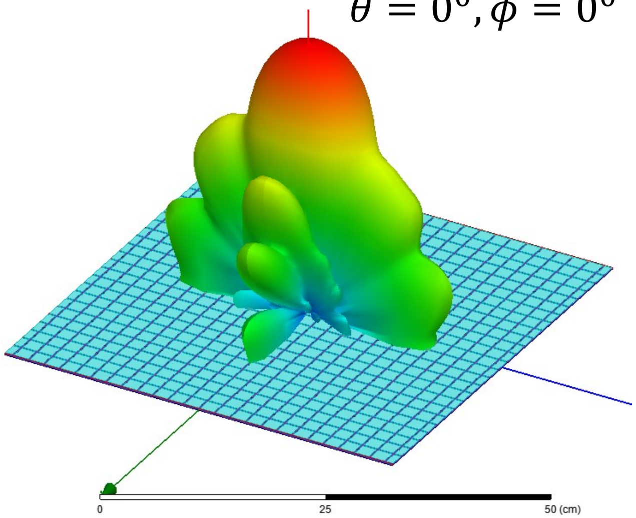
$$\beta \stackrel{\text{def}}{=} progressive\ phase\ shift$$

$$\Psi_y = kd_y sin\theta sin\phi + \beta_y$$

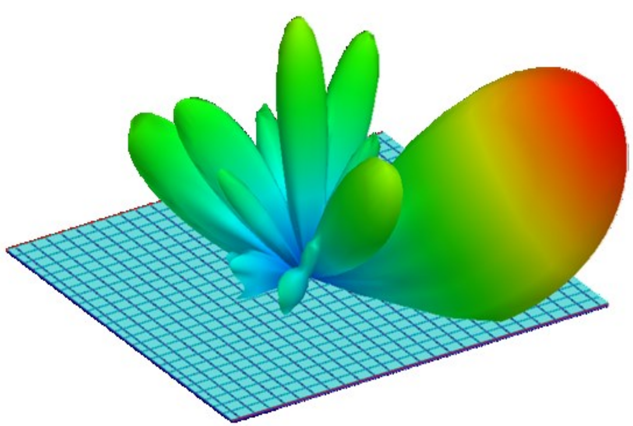
- Desirable to maximize reflection phase angle tuning range (maximum of 360 degrees) with minimal absorption (maximized S_{11})

<u>Steerable Metasurface Reflect-Array</u>

$\theta = 0^0, \phi = 0^0$



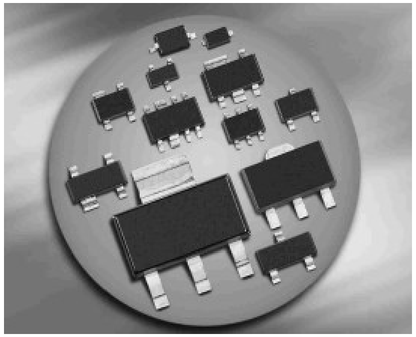
$\theta = 60^0, \phi = 30^0$



High Power Considerations / Motivation

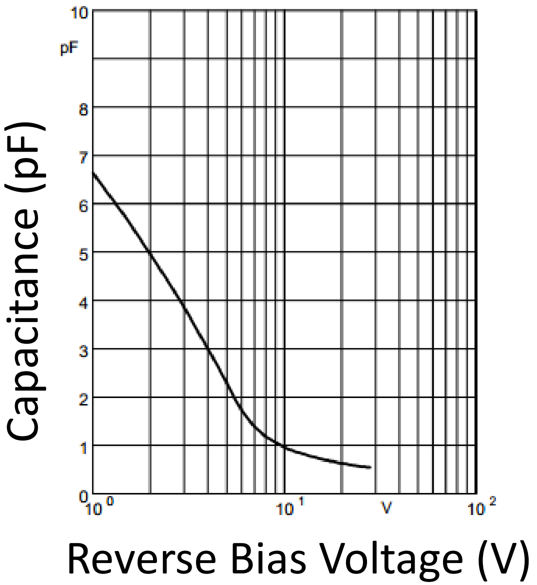
- Technical challenges
  - Size, weight, and power/gain (SWaP) of sources and antennas
  - Reliability and affordability of high power system implementation and integration
- Static metasurfaces
  - Limited by dielectric breakdown
  - Strong field enhancement at capacitive gaps
  - Avoid designs that strongly rely on resonance
- Tunable metasurfaces
  - Limited by power handling of tunable components
    - Typical tuning methods (varactor-based) insufficient for high-power applications (due to voltage breakdown)
    - Require tuning/reconfiguring method capable of withstanding high voltage levels
  - Steering time (electrical vs. mechanical)
  - Operate away from resonance
- Our objective is to present tunable metasurface designs capable of operating at higher power levels than previously demonstrated
  - Electrically tunable designs (PIN diode network, mini-cell varactor diodes)
  - Mechanically reconfigurable design (reconfigurable ground plane)

Infineon BB837 Series Varactor



Peak reverse voltage: 35 V

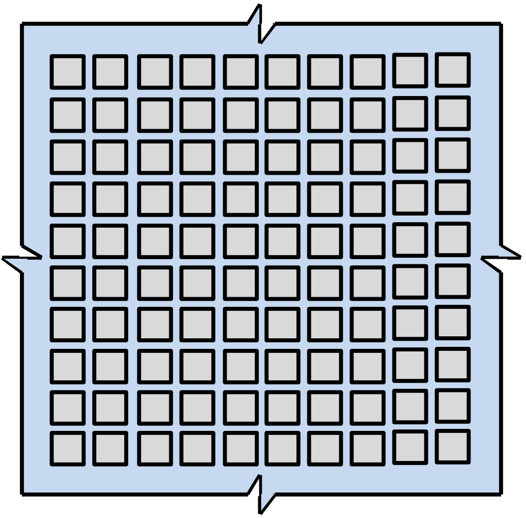
Diode Capacitance @ 1 MHz



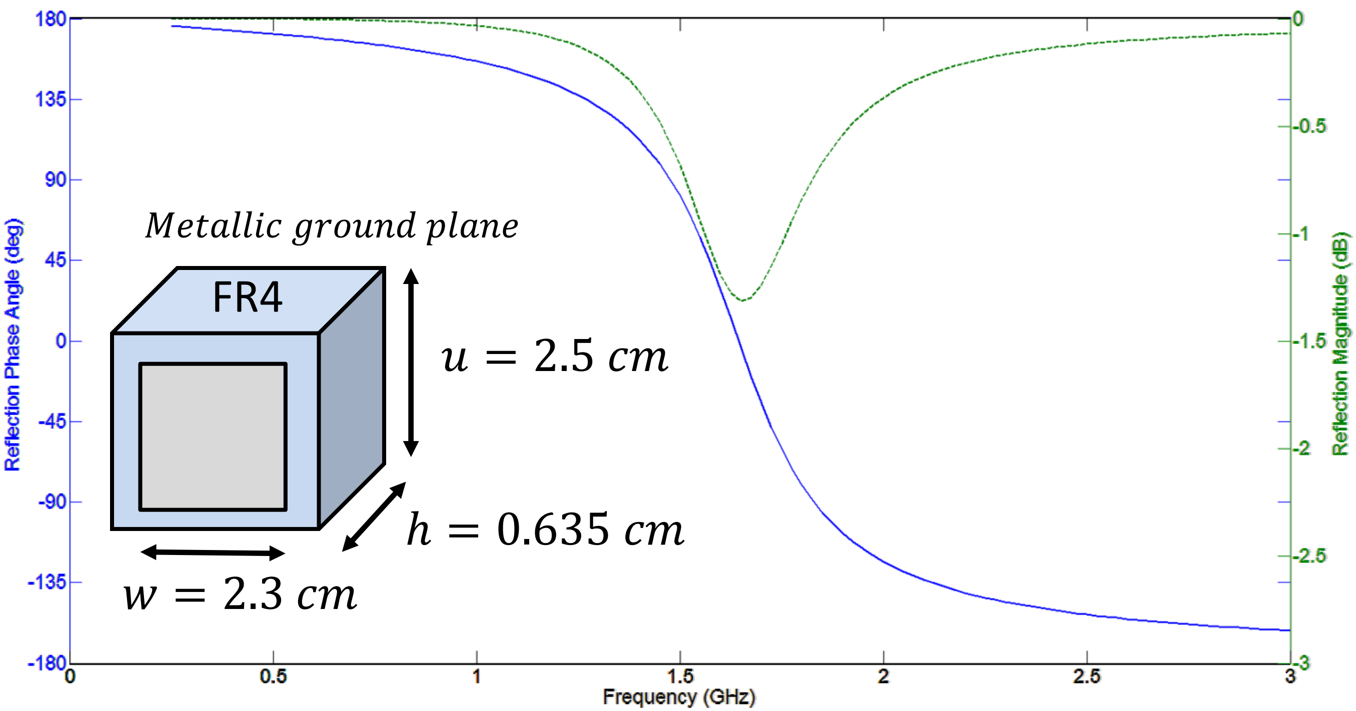
High Power Systems

ELECTRICALLY TUNABLE

Static Metasurface Design



- Fundamental design is based on the well-known Sievenpiper AMC mushroom structure
- Described by an effective surface impedance
- Static metasurface dimensions were selected such that it resonates in the desired frequency range
- Tuning achieved by altering capacitance between unit cells

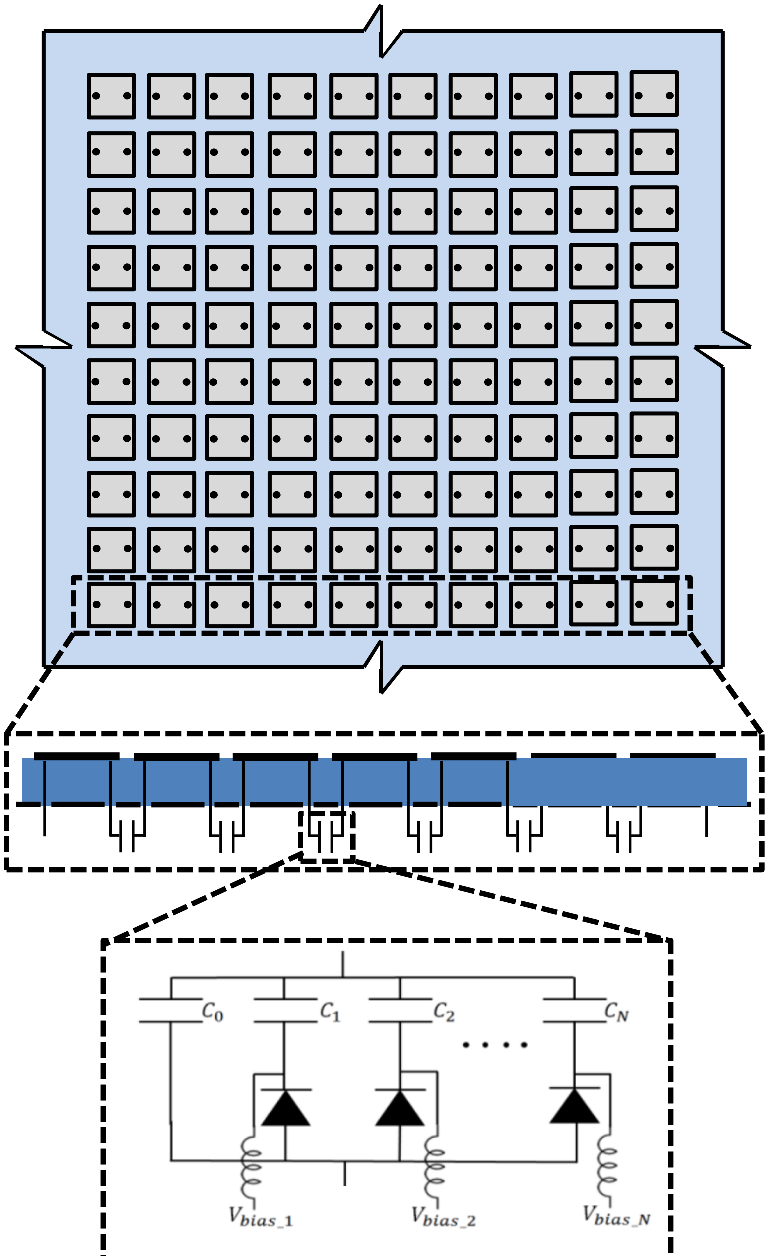


$$\omega_0 = \frac{1}{\sqrt{LC}}$$

$$Z_{surface} = \frac{j\omega L}{1 - \omega^2 LC}$$

$90°\ BW\ \ of\ \sim 15\ MHz$

PIN Diode Network Metasurface - Design

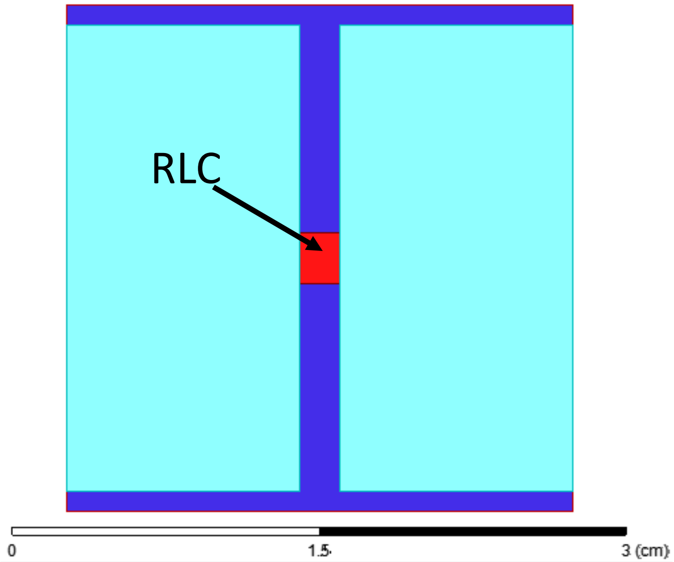


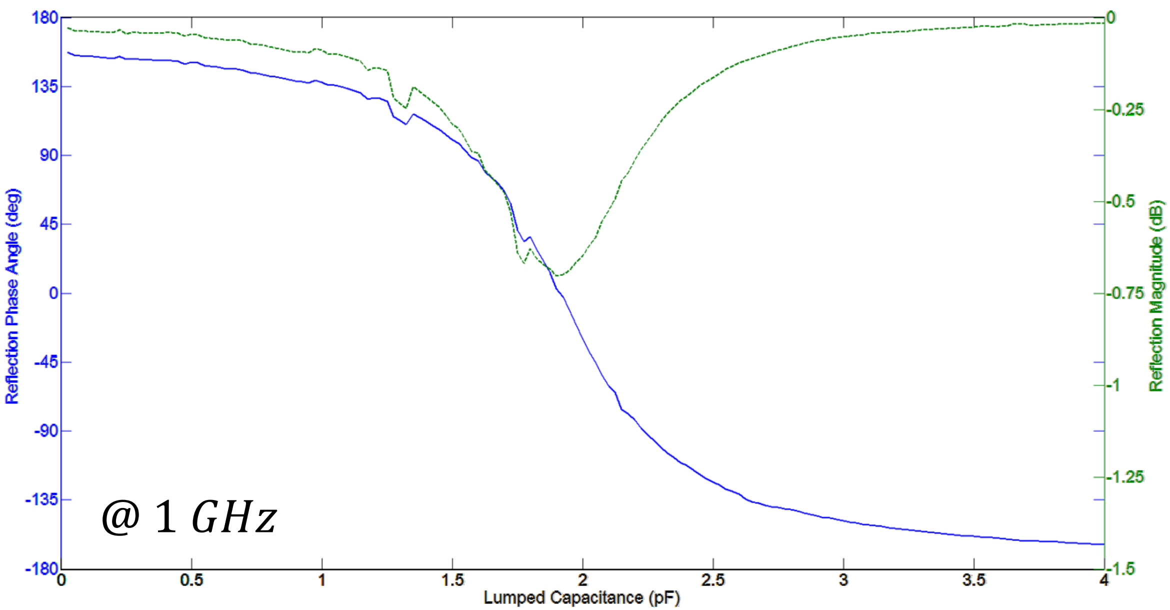
- Since tuning relies on varying capacitance we can replace varactor diodes with a capacitor network
- Ceramic capacitors can withstand voltages in excess of 1 kV
- Capacitor network controlled by RF PIN diode switches (for high speed and reliability), which can withstand much higher voltage levels than varactor diodes
- Total inter-cell capacitance can be reconfigured with 2^N possible discrete values
- Mounting beneath the ground plane with vias frees network for expansion
- Limited by cost, complexity, non-ideal parasitics

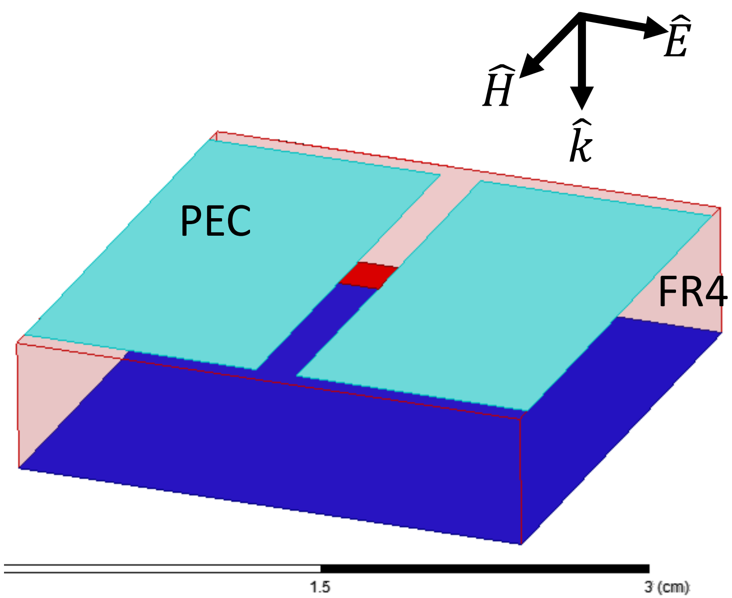
RF PIN Diodes	Peak Reverse Voltage (V)
M/A-COM MA4P505	500
Skyworks CLA4609	250
Skyworks SMP1352	200
Avago HSMP389x	100

PIN Diode Network Metasurface - Analysis

- Metasurface simulated using Ansys HFSS
- Single unit cell with periodic boundary conditions
- Normal plane wave excitation
- Linear parametric sweep of lumped capacitance values (rather than discrete values of PIN network)
- Reflection phase tuning range of approximately 300 degrees over a change in capacitance of 3.0 pF
- The capacitor network samples the reflection phase angle curve below
- Minimal absorption over band (maximum energy coupling at resonance)



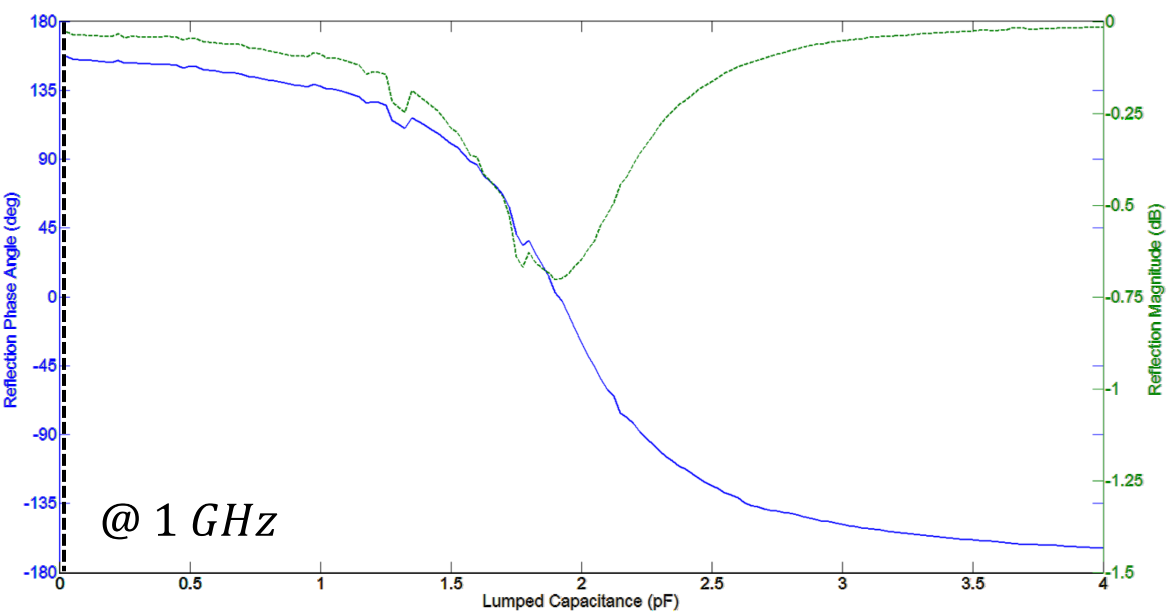




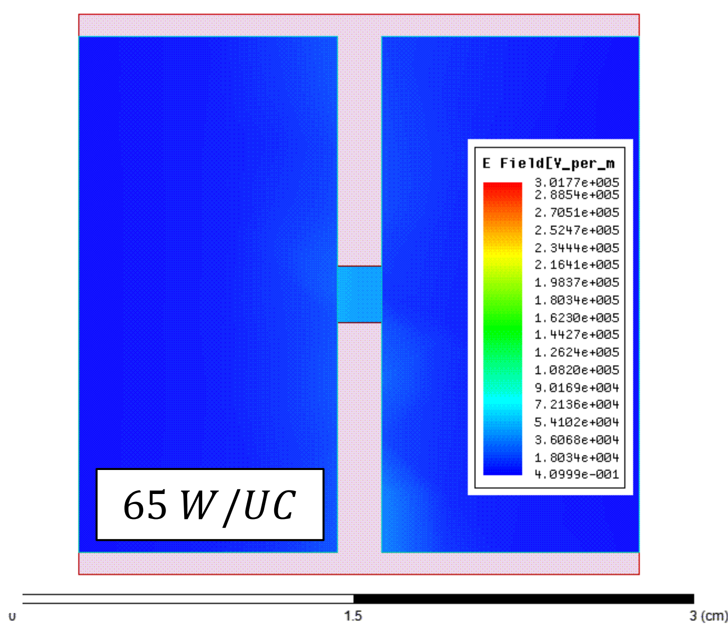
PIN Diode Network Metasurface – Power Analysis

- Incident wave induces fields on metasurface
  - Structure features strong field enhancement across lumped element
  - Operating power levels limited by voltage tolerance across tuning element
- Typical varactor diode implementation has limited power tolerance (0.25 W/unit cell)
- PIN diode network greatly extends operating power levels

Diode	Peak Reverse Voltage (V)	Max Source Power (W/Unit Cell)
M/A-COM MA4P505 (PIN)	500	30
Skyworks SMP1352 (PIN)	200	7.5
Avago HSMP389x (PIN)	100	1.9
Infineon BB837 (Varactor)	35	0.25

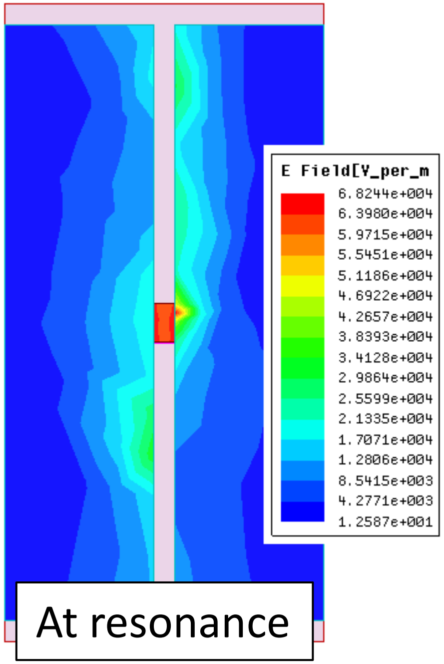


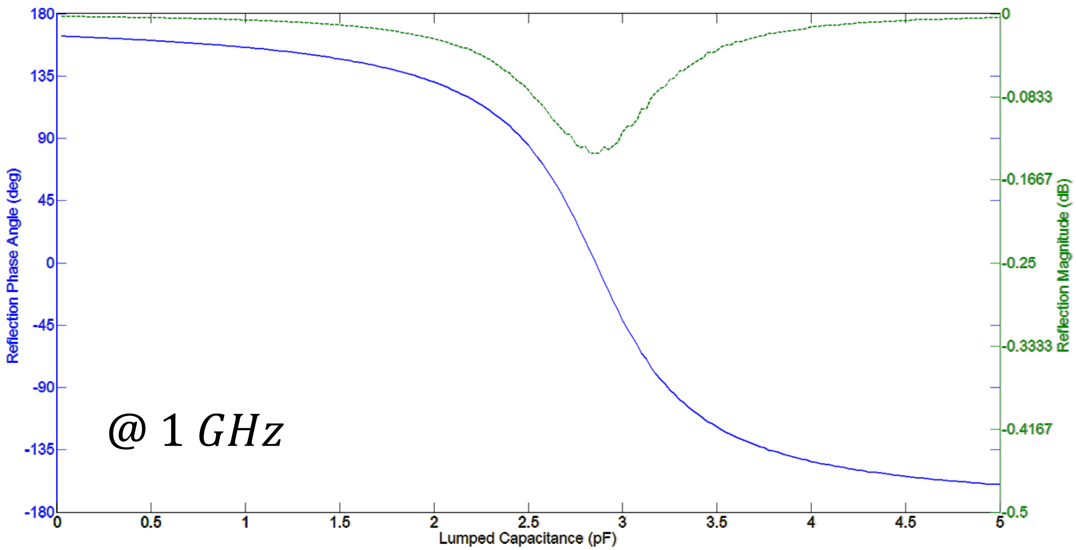
Complex Magnitude of Electric Field

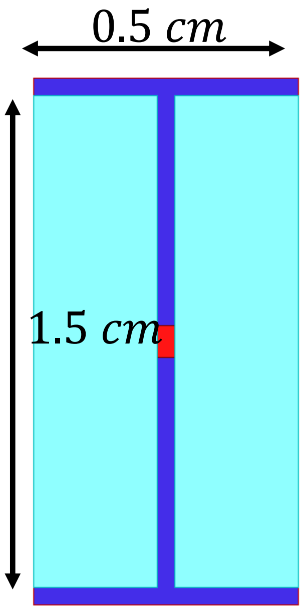


Varactor Tunable Metasurface - Design

- The complexity of implementing a PIN network tunable metasurface is undesirable
- An alternative varactor diode implementation is plausible (more restrictive in power than PIN network)
- Reflection phase angle of metasurface primarily dictated by the lumped capacitance between unit cells
  - Metasurface functionality does not rely on resonance
  - Same performance can be achieved from a smaller unit cell
- Decreasing the cell size along the E-field polarization direction increases power handling capability
- Decreasing dimension by two doubles maximum power per unit cell (to 0.5W/Unit Cell)





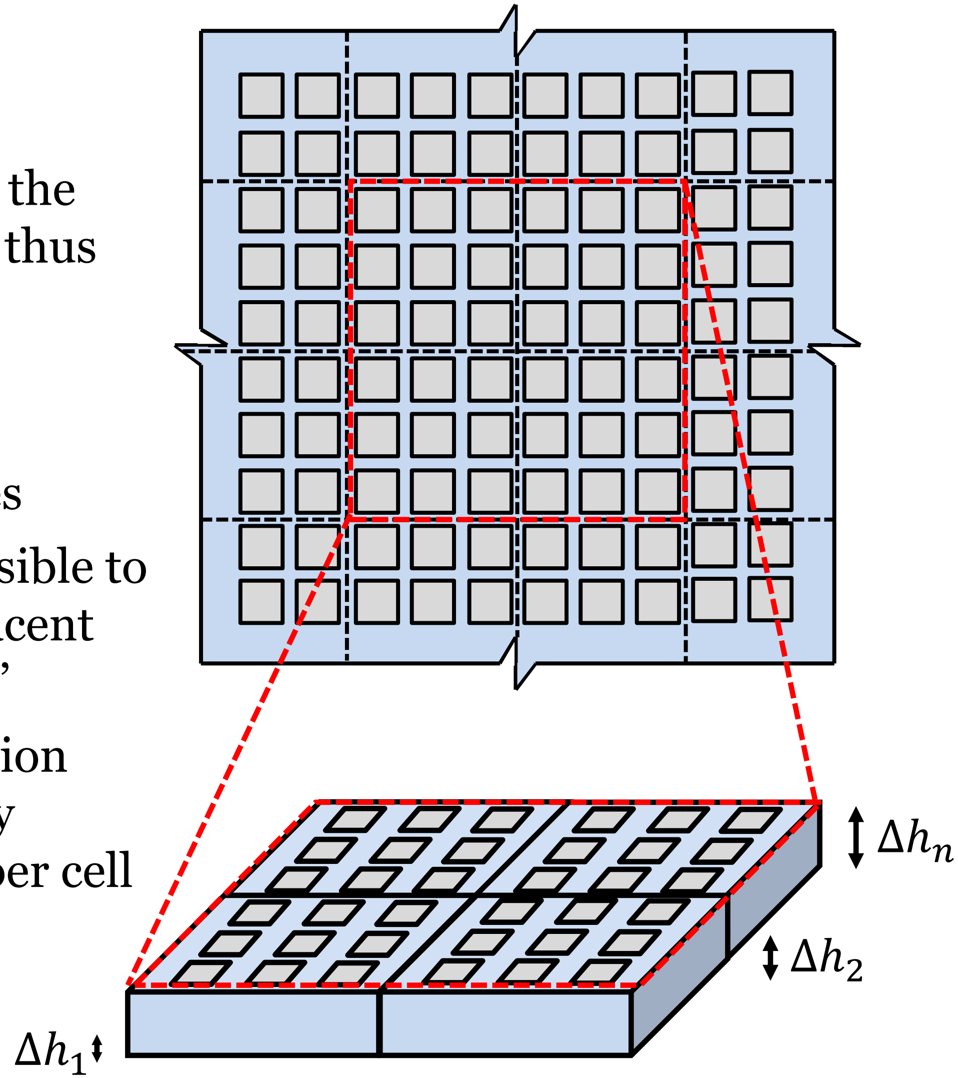


High Power Systems

MECHANICALLY RECONFIGURABLE

Reconfigurable Super Cell - Design

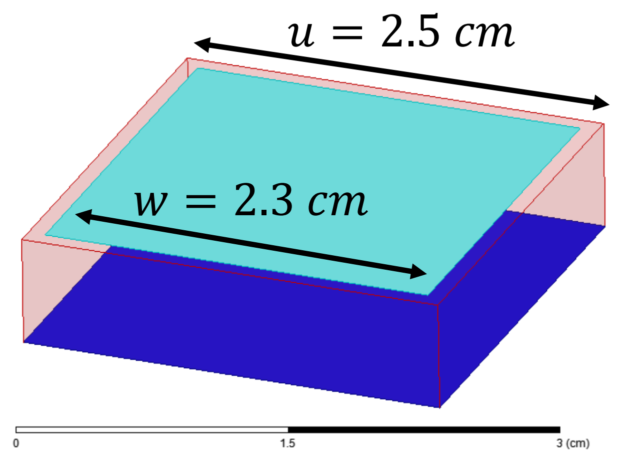
- Mechanical tuning offers possibility for operating at even higher power levels
- Varying the metasurface thickness over the ground plane alters the inductance and thus the surface impedance and resonance frequency [3]
- Ground plane can be reconfigured with miniaturized actuators or MEMs devices
- To reduce cost and complexity, it is possible to simultaneously reconfigure several adjacent cells equivalently as a single "super cell"
- Further discretizing the gradient reflection phase across a metasurface reflect-array reduces performance. However, the super cell size can be chosen accordingly to meet performance constraints



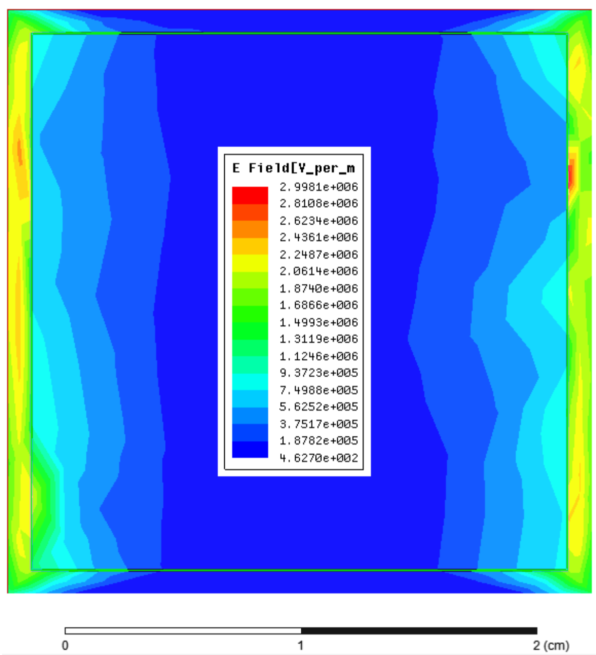
[3] D. F. Sievenpiper, J. H. Schaffner, H. J. Song, R. Y. Loo, and G. Tangonan, "Two-dimensional Beam Steering Using an Electrically Tunable Impedance Surface," *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, pp. 2713–2722, 2003.

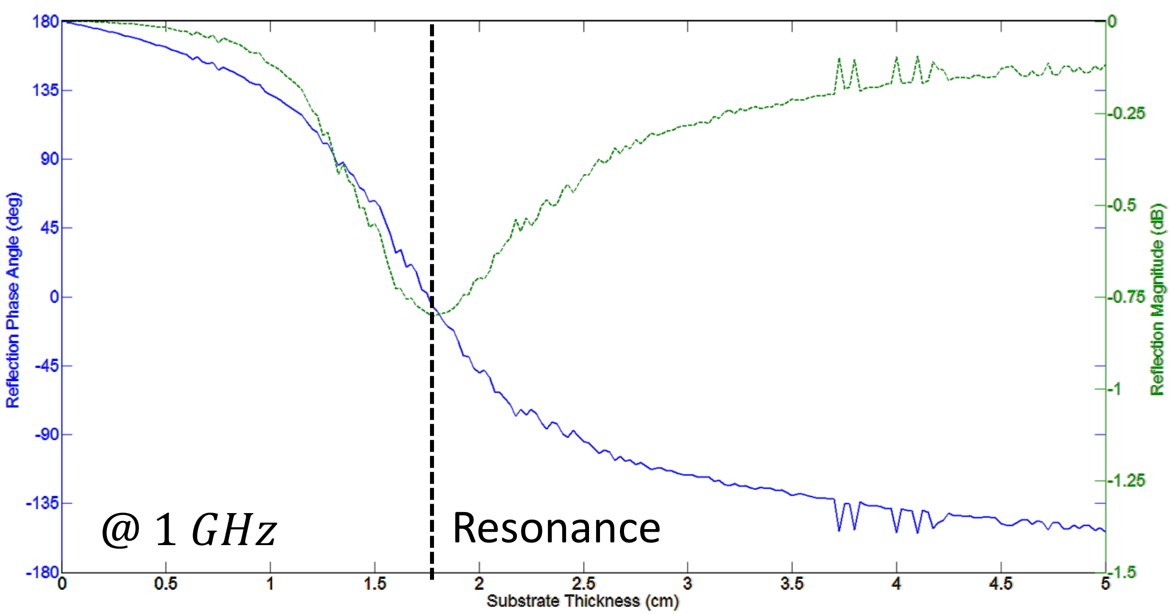
Reconfigurable Super Cell Metasurface - Analysis

- Linear parametric sweep of ground plane height
- Reflection phase tuning range of 300° over a height change of approximately 3.5 cm
- Structure features strong field enhancement across capacitive gaps
- Limited by dielectric breakdown of air (3 MV/m)
- Power handling of mechanically tunable unit cell is theoretically approx. 7 $kW/unit\ cell$ based on the field enhancement at resonance



Complex Magnitude of Electric Field





CONCLUDING REMARKS

Fabrication Considerations

- High power tunable metasurfaces are more complicated to design and fabricate than their low power counterparts due to increased complexity
- Electrically tunable designs
  - Capacitance fabrication tolerances (Δ 0.1 pF)
  - Enormously complex biasing network
- Mechanically reconfigurable design
  - Accuracy, speed, and reliability of mechanical components
  - Size, weight, and power considerations of the resulting antenna structure

Summary

- Examples that demonstrate theoretical methods for extending the operating power levels of metasurface reflectarrays have been given
- The proposed designs provide the same utility that has been previously demonstrated, however are capable of operating at much higher power levels

Future Work

- Investigate additional electrically-tunable alternatives
- Demonstrate mechanically tunable reflect-array metasurface
  - Fabrication and testing of a static prototype with predetermined super cell heights to form gradient phase distribution producing a desired reflected beam
  - Investigation of mechanical systems capable of reconfiguring ground plane without significant performance impacts

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